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DEVELOPMENT OF METEOROLOGICAL SATELLITES IN THE UNITED STATES

WILLIAM NORDBERG

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CONTENTS

DEVELOPMENT OF METEOROLOGICAL SATELLITES IN THE UNITED STATES

BASIC CONCEPT OF METEOROLOGICAL SATELLITES

The first series of meteorological satellites were devoted to the day to day identification and tracking of weather phenomena such as storms, frontal systems, jet streams, etc., on a world-wide and synoptic basis. Observations consisted initially of photographing cloud patterns with television cameras in daytime which were supplemented later by infrared radiometers to make cloud observations at night. These observations have found prominent application in short term (2-3 days) weather forecasting. The identification and tracking of weather systems by mapping world-wide cloud patterns began experimentally with TIROS I in 1960.

In a series of nine satellites from TIROS I in 1960 to TIROS IX in 1965, spacecraft technology and data transmission and processing techniques advanced progressively so that daytime cloud photographs were acquired daily over the entire globe. In February 1966, the launch of ESSA I initiated the series of TIROS Operational Satellites (TOS) which began to carry out global cloud photography operationally and routinely for the Environmental Science Services Administration (ESSA).

Very early in the development of TIROS it became apparent that adequate nighttime cloud sensors, such as the High Resolution Infrared Radiometer (HRIR), and the direct transmission of cloud photographs to local facilities via the Automatic Picture Transmission (APT) system, required a larger, more versatile spacecraft than TIROS. Such spacecraft also had to accommodate experiments not necessarily devoted to the tracking of cloud formations, but rather to explore the many, as yet, ill-understood processes which are known to have a strong bearing on weather. For example, it was desirable to continue the monitoring of the global distribution of net radiation flux; i.e., the energy difference between solar radiation absorbed and telluric radiation emitted by the Earth's surface and the atmosphere. Such measurements had already been made with Explorer VII launched in October 1959 (Weinstein and Suomi, 1961) and with TIROS. Also on TIROS, experiments were developed to infer the stratospheric circulation, global distribution of water vapor and Earth surface temperatures from radiometric measurements. To carry all these experiments and to provide for their continued expansion and development we began, in 1960, the design of the NIMBUS spacecraft. This was an extremely important step, as it permitted us to pursue the implementation of an immediate operational observation system based on TIROS while, at the same time, NIMBUS provided the potential and capacity to conduct scientific investigations and to develop sensors and technology which might eventually be employed in a "second generation" operational

system. The operational requirements for acquiring cloud observations to make forecasts were thus kept from interfering with the development of more advanced observation techniques to which NIMBUS, as a versatile and flexible meteorological observatory, was tailored.

One shortcoming of cloud observations with the TOS system could not be overcome with NIMBUS. The observation of small-time scale meteorological phenomena, such as severe storms, required almost continuous observations of the same area over periods of several hours. Such observations are only possible when made from a spacecraft in geostationary orbit; i.e., from an altitude of about 37,000 km. From that orbit, we observe not only small scale phenomena continuously but we also track cloud formations on a synoptic scale more effectively so that in appropriate circumstances we can make wind measurements. For this purpose, two of NASA's Application Technology Satellites (ATS) were instrumented with scanning photometers so that each satellite produced daytime images of cloud cover over one-third of the globe (McQuain, 1967). The first ATS was successfully launched in December 1966 and has the capability of transmitting a picture of the Earth's "disc" over the Pacific once every twenty minutes. The other, ATS III, was launched in November 1967 and is capable of transmitting color pictures at similar intervals for the Atlantic region (Warnecke and Sunderlin, 1967). In contrast to TIROS and NIMBUS, ATS were not developed specifically to make meteorological observations and they carry several experiments for other purposes. Nevertheless, they play an important role in our meteorological satellite program and their cloud cover observations serve a purpose which could not be fulfilled with the TIROS and NIMBUS satellites.

Because of the great capacity of NIMBUS for meteorological experiments and because of the impact which such experiments may have on future developments of the Global Atmospheric Research Program, we shall discuss the NIMBUS concept and system in greater detail.

NIMBUS—A SERIES OF GLOBAL METEOROLOGICAL OBSERVATORIES

The same, rather sophisticated, basic spacecraft system concept is employed in each of six NIMBUS missions; two of which have been carried out; two others are in preparation for launch during 1969 and 1970, respectively; and two more are being planned for launch after 1971. This basic concept includes: a spacecraft capable of delivering in the order of 200 watts of electrical power to the experiments; a mechanical structure which can accommodate a maximum number of experimental instruments and which can be pointed at the Earth at all times with an accuracy of about 1°; a stable and moderate thermal environment required by many instruments; a data system which can acquire and store in the order of 10^9 to 10^{12} bits per orbit and transmit these data to the ground while

passing over Alaska, and in addition, can transmit continuously a lesser amount of data. The NIMBUS concept also calls for observation of practically all points on the globe at least twice during every 24 hour period, always at the same local time. This is accomplished by placing the spacecraft into a "sun synchronous" orbit at a height of about 1100 km. Thus, the orbit plane is inclined to the equator 98.7 degrees and precesses around the center of the Earth at a rate that is synchronous with the revolution of the Earth around the Sun. As a consequence, the relative orientation between the orbit plane and the sun remains essentially constant and the satellite crosses the equator always at noon and midnight.

Although the basic NIMBUS concept remained the same for six spacecraft (Figure 1), many of the spacecraft subsystems are being improved from spacecraft to spacecraft to provide greater accuracy, reliability or, most importantly, to accommodate a changing and ever increasing complement of experiments.

The first two missions, NIMBUS I launched in August 1964 and NIMBUS II launched in May 1966, carried experiments to:

a. Demonstrate improvements in making high resolution daytime cloud observations;

b. Demonstrate the feasibility of high resolution nighttime cloud mapping;

c. Transmit both day and nightime cloud images to local receivers;

d. Map emitted telluric radiation as well as reflected solar radiation, in various spectral bands.

The sensors consisted of:

a. A set of three television cameras and a tape recorder called the Advanced Vidicon Camera System (AVCS) for daytime cloud photography.

b. A scanning High Resolution Infrared Radiometer (HRIR) to map and image thermal radiation emitted between 3.4 and 4.2μ by cloud tops or the Earth's surface. On NIMBUS II, HRIR images were transmitted also via the APT.

c. An additional television camera to transmit daytime cloud pictures via the APT to simple, inexpensive and often "homemade" receivers.

d. A scanning, five channel Medium Resolution Infrared Radiometer (MRIR) to map and image thermal radiation emitted by atmospheric water vapor or cirrus clouds between 6.4 and 6.9μ, by CO_2 in the lower stratosphere between 14 and 16μ, by cloud tops or by the Earth's

surface between 10.5 and 11.5μ, and by the Earth's surface as well as by the atmosphere between 5 and 30μ. Reflected solar radiation between 0.2 and 4.0μ was mapped with the fifth channel. This instrument was carried on NIMBUS II only.

NIMBUS I produced observations covering almost the entire globe every 24 hours with the AVCS and ATS experiments, and every 12 hours with the HRIR experiment. These observations ceased four weeks after launch when the mechanical drive for the paddles carrying the solar cell power source malfunctioned. Similar AVCS observations were obtained with NIMBUS II from 15 May to 31 August 1966. HRIR observations, stored for each orbit and retransmitted to the primary Data Acquisition Station in Alaska as well as transmitted directly via APT over the whole world, were made from 15 May to 15 November 1966. The MRIR provided global maps of radiation intensities for all five channels from 15 May to 28 July 1966. In each case, observations ceased because the tape recorder associated with each experiment ceased to operate. Daytime cloud pictures from the APT television camera, which was independent of any tape recorder, were transmitted world-wide to about two hundred receivers for almost two years.

The HRIR demonstrated not only that cloud formations can be observed globally at night with a spatial resolution of about 8 km, but, also, that cloud heights can be inferred from the measured cloud top temperatures. Thus, at night, the HRIR produced "3-dimensional" global cloud maps which were not attainable with television cameras. The 10.5-11.5μ channel of the MRIR also produced these cloud cover and height maps but during day <u>and</u> night and with considerably lesser spatial resolution (50 km). Based on this technology, there will be a high resolution 11μ scanning radiometer on ESSA's "second generation" TIROS Operational Satellite for day and night operational cloud mapping, globally as well as by transmission via the APT system.

A major new approach to the synoptic mapping of large scale weather patterns was demonstrated by simultaneous analyses of the 10.5-11.5μ and the 6.4-6.9μ channels of the MRIR (Nordberg et al. 1966). The moisture and cloudiness contrast in the two channels (Figure 2) could be interpreted as indications of large scale vertical motions and of dynamic activity. The course of the jet streams, with rising air on the equatorward side and subsiding air on the poleward side of the core, could be traced especially well.

In cloud free areas, the HRIR mapped temperatures of the Earth's surface with sufficiently great accuracy to permit the tracking of ocean currents (Figures 2 and 3).

Analysis of the combined measurements in the 5-30μ and 0.2-4.0μ channels and of the 14-16μ channels of the NIMBUS II MRIR provided significant new insights into two important atmospheric processes: the global distribution of net

radiative energy flux through the upper boundary of the atmosphere (Raschke and Pasternak 1967) and the morphology of the circulation in the lower stratosphere (Warnecke and McCul[illegible]h 1967). Examples for these analyses are shown in Figures 5 and 6 respectively.

SOUNDING THE ATMOSPHERE WITH NIMBUS III AND IV

Experiments on NIMBUS I and II were devoted exclusively to improve the synoptic mapping of meteorological phenomena or to make atmospheric measurements of general scientific interest. The success of modelling the general circulation of the atmosphere mathematically, which came to fruition recently through the facility of large computers, now placed an entirely different requirement on satellite observations: It called for the global description of the atmospheric mass and wind fields at various height levels. For, if such a description were obtained, it could be used mathematically as the initial state of the atmosphere from which its future state could be computed. Thus, mathematical weather predictions, possibly over periods of two weeks, might become feasible.

Unfortunately, the only applicable parameter which at this time lends itself to measurement from satellites is the temperature variation with height in the troposphere and lower stratosphere. Even that measurement may be seriously compromised by the varying cloud cover. But still, based on existing sensor and spacecraft technology, this is the most promising measurement to be made. Temperature as a function of height in the atmosphere might be inferred from measurements of radiation emitted by a gas, such as CO_2, which is uniformly mixed with air. Measurements must be made spectrally; i.e., at several wavelengths within the absorption (emission) band of the gas. The derivation of temperature is based on the concept that the spectral radiance (which is related to the temperature of the gas) observed by the satellite at various wavelengths corresponds to different height levels, depending on the transparency of the gas at a given wavelength. This concept is illustrated in Figure 7 where the spectral radiance measured near the edge of the carbon dioxide band, indicating a temperature of about 290°K near wave number 800 cm^{-1}, corresponds to a temperature near the surface, while the temperature of 230°K at the center of the absorption band near 670 cm^{-1}, where carbon dioxide is most opaque, corresponds to the maximum height, several kilometers above the tropopause. The temperature reversal at the tropopause is clearly indicated in the spectrum near 620 and 700 cm^{-1}. The atmospheric mass field, i.e., the variation of density with latitude, longitude and height could be computed from the measured temperature profiles, provided that pressure at a given level, preferably the surface, is known. Surface pressure could be measured by automatic sensors distributed worldwide and transmitting their data to a satellite.

Measurement of wind from satellites is very difficult and, so far, has been successful only under severe limitations, through inference from cloud observations with the ATS. Wind measurements from lower altitude satellites might be performed by tracking free floating balloons globally at various height levels. Eventual operational systems will probably combine both techniques to arrive with a satisfactory description of the wind field.

On the basis of these requirements and assessments, two spectrometer experiments capable of measuring the vertical temperature structure and one experiment capable of relaying measurements from automatic stations and of tracking balloons were selected for flight on NIMBUS III. One spectrometer is a Michelson Interferometer called Infra-Red Interferometer Spectrometer (IRIS) and operates between 6 and 20μ at a relative spectral resolution of 1:200. Included within this spectral interval are the water vapor absorption band centered at 6.3 microns, the 9.6 micron ozone band, and the 15 micron carbon dioxide band. Hence, information on atmospheric water vapor and ozone as well as vertical temperature structure should be available from these data. The second spectrometer, the Satellite Infra-Red Spectrometer (SIRS), is a modified Fastie-Ebert grating spectrometer. Radiant energy is detected in seven spectral intervals of the 15μ CO_2 band. The spectral intervals are 5 cm^{-1} wide. The eighth channel senses radiation in the atmospheric window, centered at 11.1μ.

The data relay and balloon tracking experiment, called Interrogation, Recording and Location System (IRLS) consists of a satellite-borne transmitter, receiver, and computer which, by communication with a given automatic ground station, can determine the location of the station within about 2 km and can also interrogate a set of sensors, such as a thermister, contained in the station.

Four additional experiments have been selected for flight on NIMBUS III. Three of these will continue the mapping observations of NIMBUS I and II: the HRIR, MRIR and the Image Dissector Camera System (IDCS) which is an improved television camera. The fourth, Monitor of Ultraviolet Solar Energy (MUSE), will expand the capability of NIMBUS to perform scientific investigations relevant to meteorology. MUSE will measure solar radiation in five, 100A wide spectral intervals ranging from 1200A to 2600A. Variation in that radiation might have a strong bearing on the energy input into the stratosphere.

The first launch of NIMBUS III was attempted on 18 May 1968, but failed because of a malfunction in the launch vehicle. Another launch will be attempted in 1969.

A complement of nine experiments on NIMBUS IV will continue the pursuit of the three major objectives: atmospheric structure measurements for mathematical prediction models, basic scientific investigations, and mapping of horizontal fields; in that order of priority. The emphasis on the first objective is

indicated by the fact that four experiments will be capable of temperature soundings and three of the four will also measure vertical distribution of water vapor: the IRIS with its spectral range extended to 8–40μ; the SIRS with the addition of 6 spectral intervals, mostly in the rotational water vapor band between 18 and 30μ; and a Filter Wedge Spectrometer (FWS) operating between 1.2 and 6.4μ. The other temperature sounder is a Selective Chopper Radiometer (SCR) operating in the 15μ CO_2 band and is expected to achieve a very high spectral resolution by filtering the radiation through carbon dioxide absorption cells. The IRLS experiment will be expanded to be capable of interrogating hundreds of stations instead of 20 on NIMBUS III. Also, a balloon experiment will be performed to measure the wind field at at least one height level over a large selected region, such as the tropics; while on NIMBUS III, only an engineering test of the system, involving less than six balloons over the United States, will be performed.

Scientific investigations will be further expanded with NIMBUS IV. A Backscatter UltraViolet (BUV) spectrometer will measure the intensity of solar radiation reflected by the atmosphere in 14 intervals, each 10A wide, over the spectral range from 2500 to 3400A. The global vertical distribution of ozone at heights from 15 to 50 km will be derived from these measurements. The MUSE experiment will be continued and its value will be enhanced by combining it with the BUV measurements.

Measurements of horizontal water vapor and cloud fields will be greatly improved by a scanning Temperature and Humidity Infrared Radiometer (THIR) operating in the 6.3μ water vapor and the 11μ window bands with a spatial resolution of the HRIR. The IDCS will continue to provide television pictures for reference purposes.

It is expected that the experiments on NIMBUS IV, for which early test models exist already, will be flown by 1970.

Plans are now being made for the development of two more NIMBUS spacecraft to be launched after 1971. They might extend the earlier experiments for both vertical sounding of the atmosphere and mapping of horizontal fields into the microwave spectrum. The same principle as in the infrared holds for sounding and mapping at longer wavelengths, except that microwave emission from clouds is confined essentially to dense water clouds. Thus, vertical temperature soundings in the microwave spectrum will suffer from considerably lesser interference by cirrus and stratus clouds and by haze than in the infrared. Oxygen, at wavelengths near 0.5 cm, serves as the emitter analogously to the 15μ CO_2 emission. Water vapor can be observed at 1.35 cm and heavy clouds or rainfall could be mapped at wavelengths between 1.5 and 1.8 cm. These spacecraft may also carry experiments to expand scientific investigations, especially, for example, by studying the interface between the ocean surface and the atmosphere and interactions between various atmospheric levels.

OUTLOOK

Results from the NIMBUS and ATS experiments will be applied to develop a "second generation" operational meteorological satellite system in the United States. Also, based on the experience gained from NIMBUS and ATS experiments, satellite observations could be designed specifically to apply to the Global Atmospheric Research Program (GARP) and to the World Weather Program (WWP). The problem is to define the most suitable observations required by these Programs and to conduct the operation cost-effectively. This must be accomplished in the near future through the cooperation of appropriate international organizations. The necessary technology is certainly available. For example, a simple meteorological satellite (simpler than the present ATS), at geosynchronous altitudes could support a regional (tropical) GARP experiment by observing cloud cover continuously and by relaying data from surface and airborne platforms. A more extensive global experiment could be supported by a series of such geosynchronous satellites plus a low altitude spacecraft in a high inclination orbit, but simpler than NIMBUS, to perform vertical soundings.

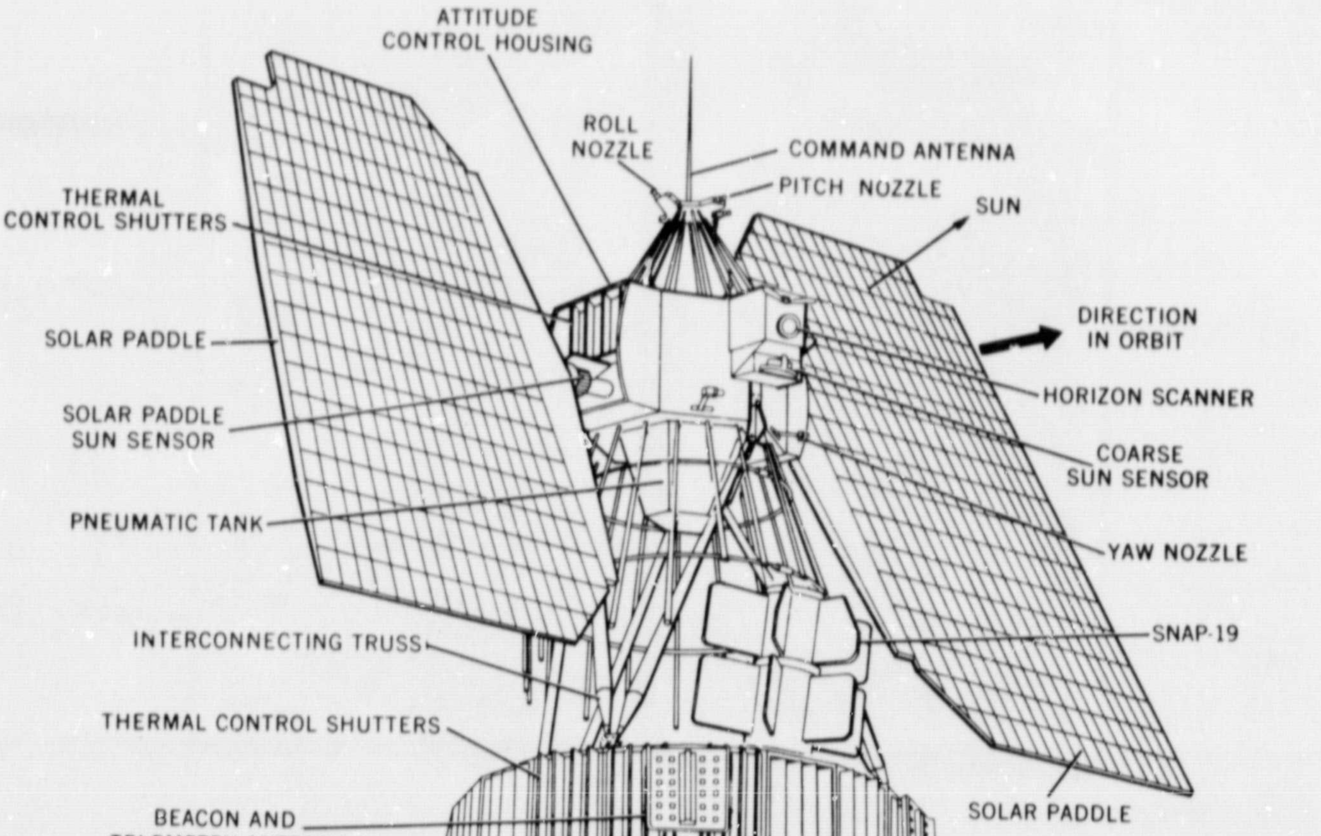

Figure 1. The NIMBUS III Spacecraft

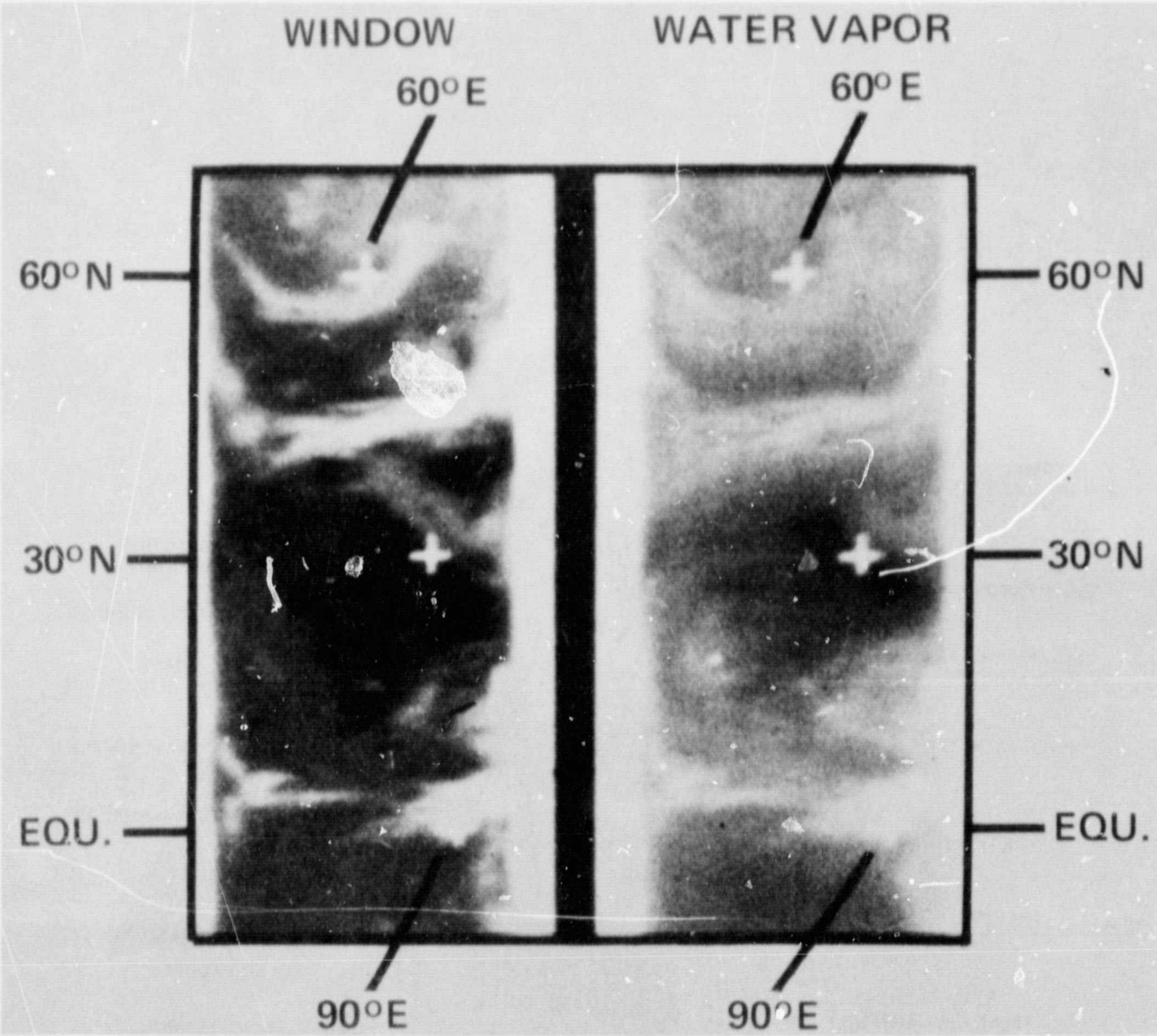

Figure 2. Maps of emitted radiation in the window (10.5 to 11.5μ, left) and by atmospheric water vapor (6.4 to 6.9μ, right) obtained over India on 17 May 1966 with the NIMBUS II MRIR. Darker shades indicate more intensive emitted radiation than lighter shades. In the window channel, the radiation intensity is proportional to the cloud top or surface temperature. In the water vapor channel, radiation decreases with increasing concentration of water vapor in the upper troposphere or with increasing height and density of cirrus clouds.

In the window channel, the warmer Indian subcontinent is contrasted against the colder ocean. The Himalaya mountains show very cold temperatures. In the water vapor channel low radiation intensities are seen over the entire area with no contrast between land and ocean. This must be caused by high water vapor content in the upper troposphere or by cirrus cloud coverage, both implying strong upward motion. The warmest (driest) region is confined to a narrow band extending from northwest to southeast exactly along the southern edge of the mountains, aligned with the Ganges River Valley. This suggests subsiding dry air along the mountains. To the north, over central Asia, two intense, high altitude cloud bands, apparently associated with fronts, can be seen in both channels.

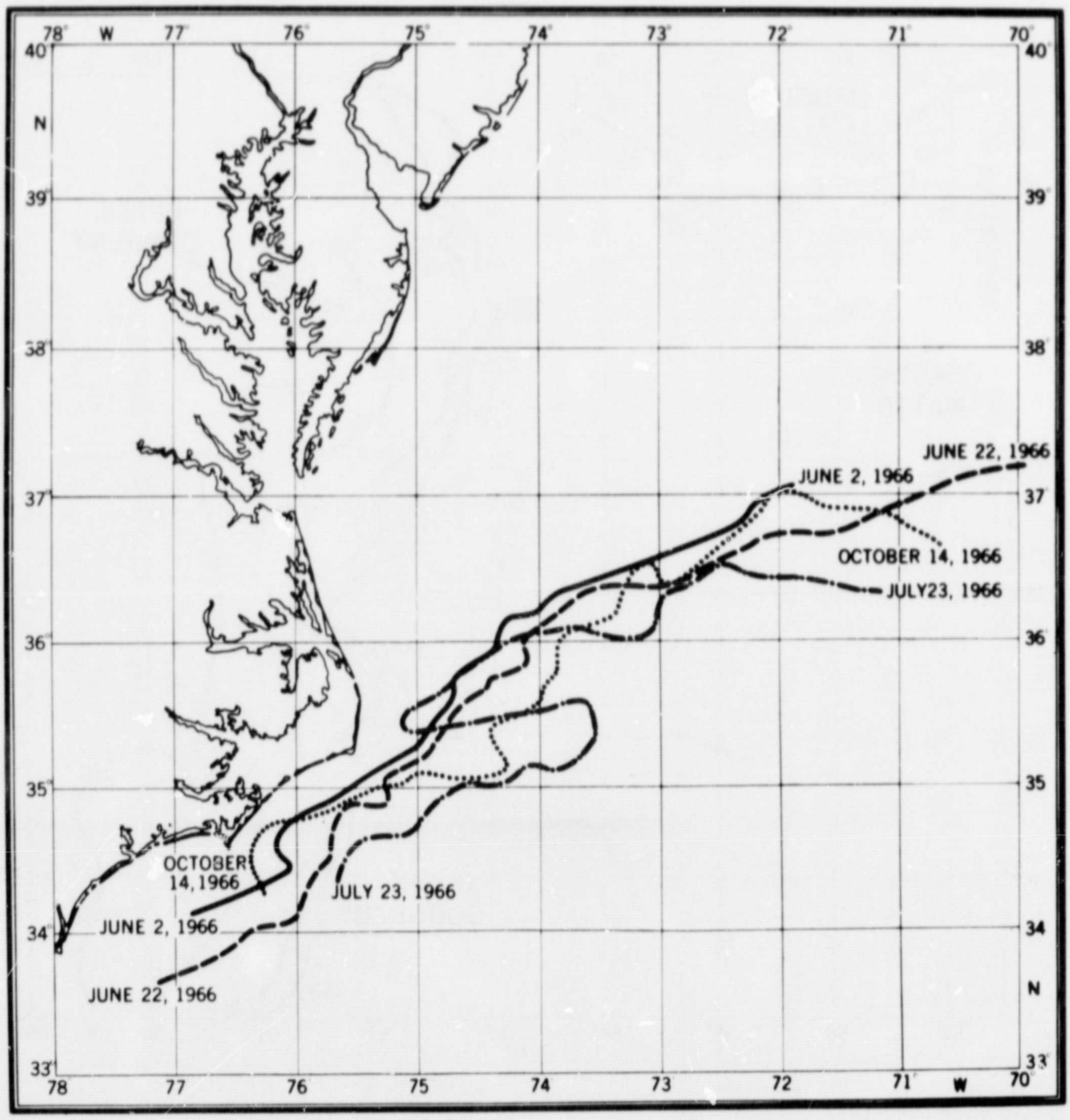

Figure 3. Gulf Stream Boundary Positions Derived from NIMBUS II HRIR Measurements from June through October 1966 (After Warnecke et al. 1967)

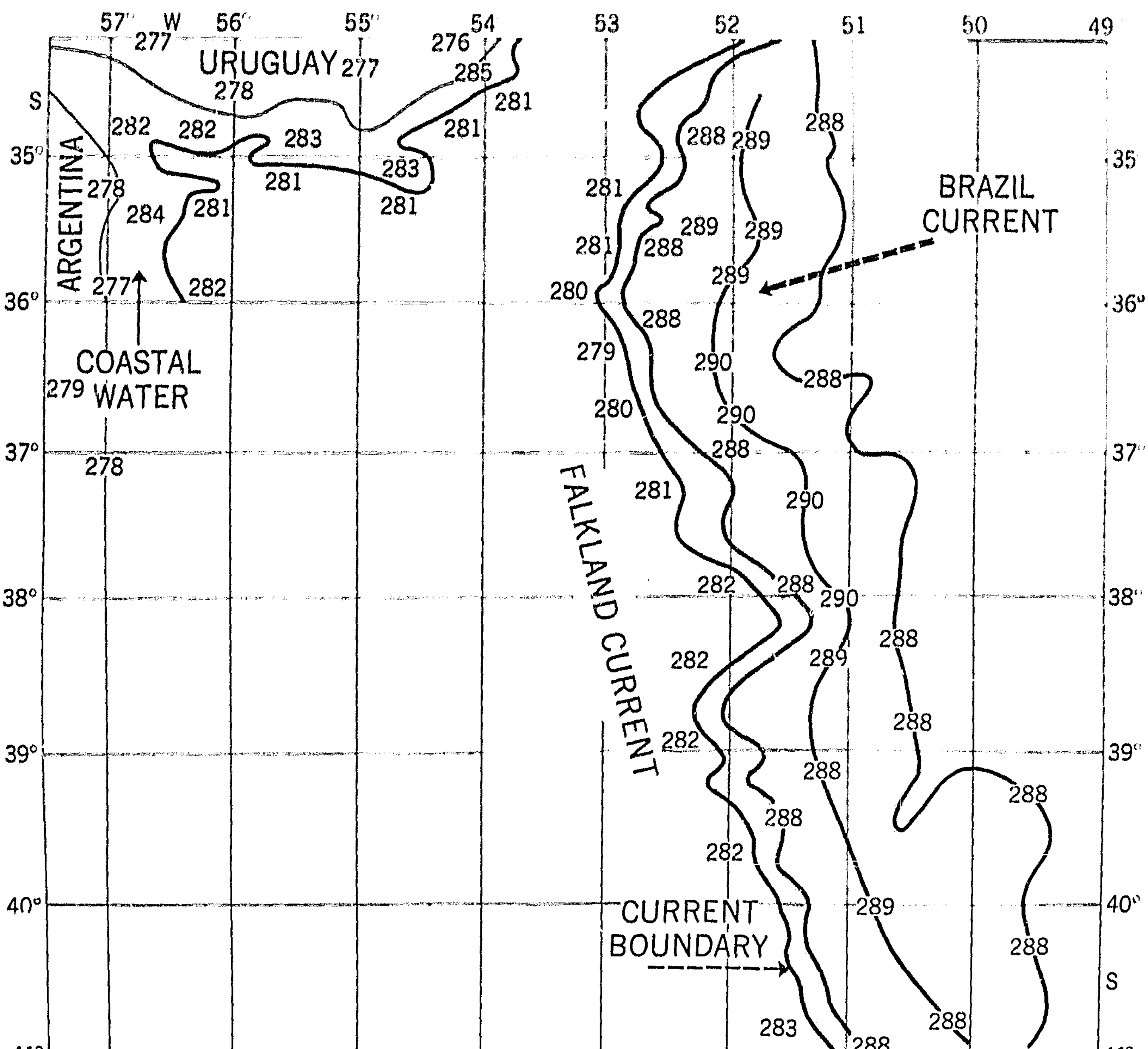

Figure 4. Falkland and Brazil Current Boundary on August 17, 1966, From NIMBUS II HRIR Measurements (After Warnecke et al. 1967).

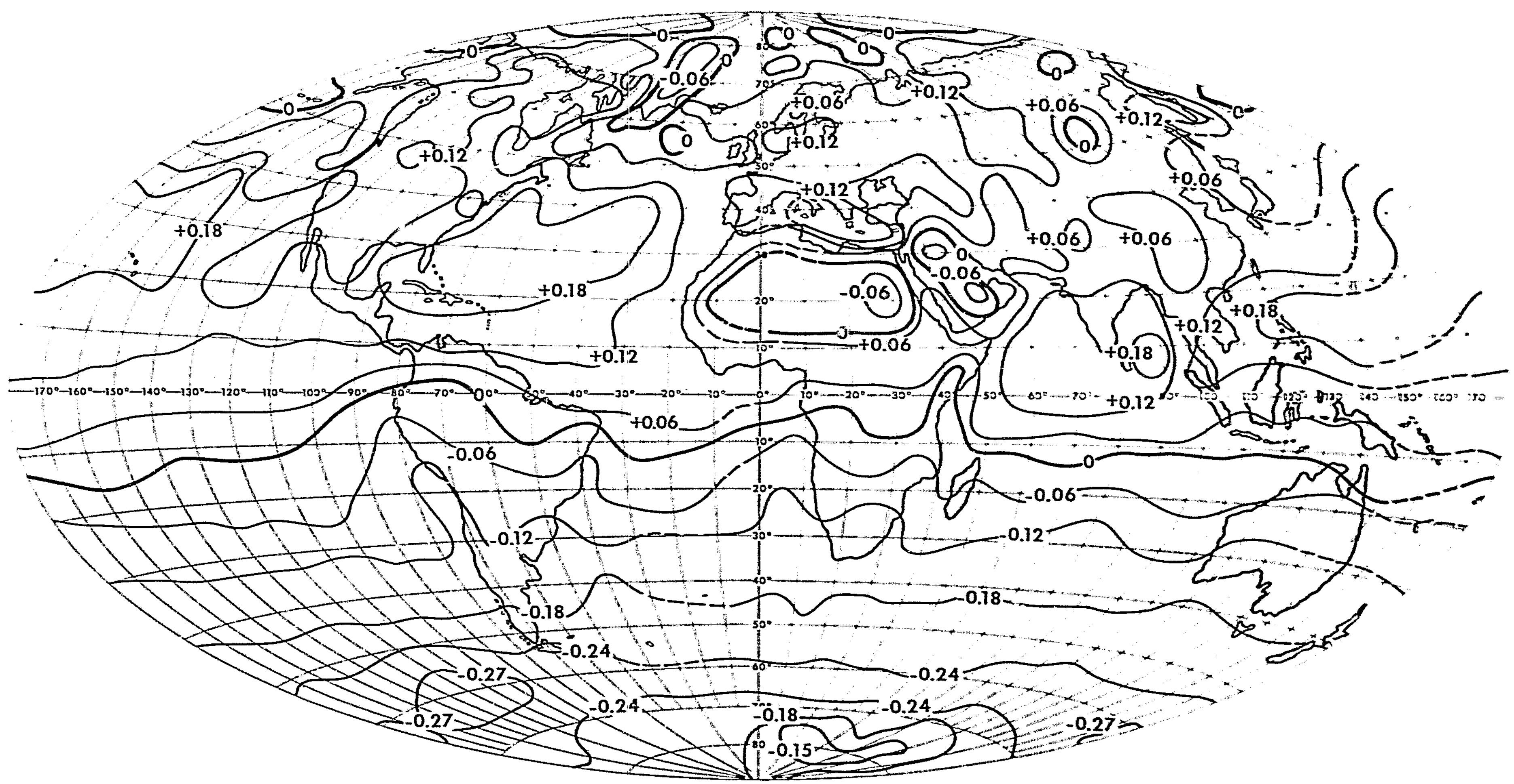

Figure 5. Net radiation flux [cal cm^{-2} min^{-1}] during the period 1–15 July 1966 observed with NIMBUS MRIR. Energy surplus of absorbed solar radiation over emitted longwave radiation (net downward flux) is found generally north of 10°S. Surplus maxima occur over the relatively cloudless northern subtropical oceans. The large desert areas of North Africa and Arabia, in contrast, show a deficit (upward flux). This deficit is caused by the high albedo (30% to 40%) and by the high surface temperature of those areas. There is also energy deficit over the Arctic land and ice areas. South of 10°S, there is consistent energy deficit. (After Raschke and Pasternak, 1967)

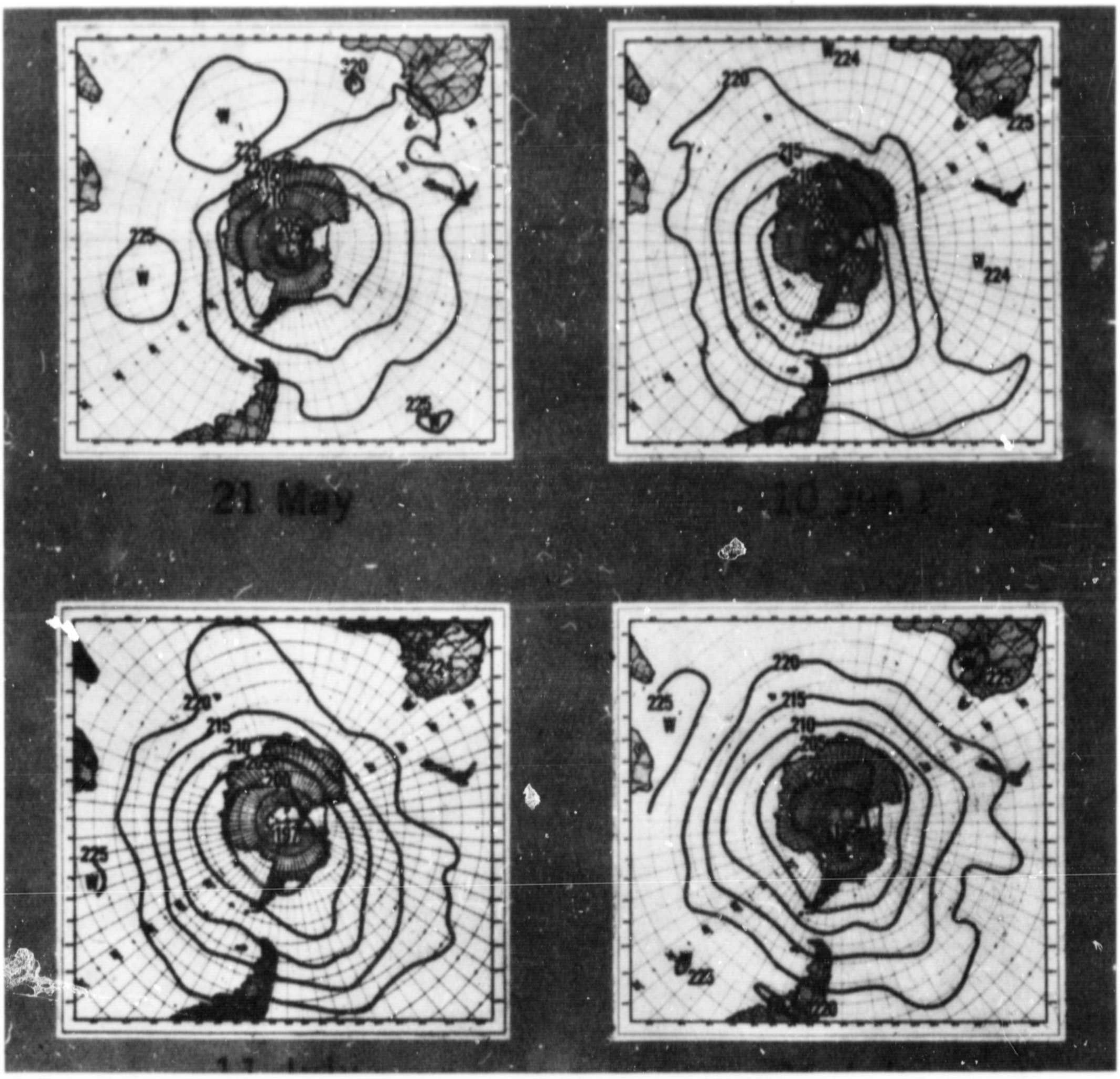

Figure 6. Radiation emitted in the 14-16μ band measured by the NIMBUS II MRIR over the southern hemisphere on 21 May, 10 June, 11 July and 24 July 1966. Radiation intensities are expressed as temperatures (^{o}K) of a blackbody emitting the equivalent amount of radiation within this spectral band. The measured radiation is emitted primarily in the lower stratosphere and, in this region, is a good indicator of the relative horizontal temperature field and of the general circulation.

On May 21, 1966, the southern polar vortex (upper left) was well established and located over the South Pole. It was, however, asymmetric. 20 days later (upper right) the temperature asymmetry was almost reversed and the cold air center cooled by 5^{o}K. On 11 July (lower left) the temperature over the South Pole dropped by 3 more degrees. Finally, on July 24 (lower right), the temperature distribution became symmetric around the Pole. (After Warnecke and McCulloch 1967)

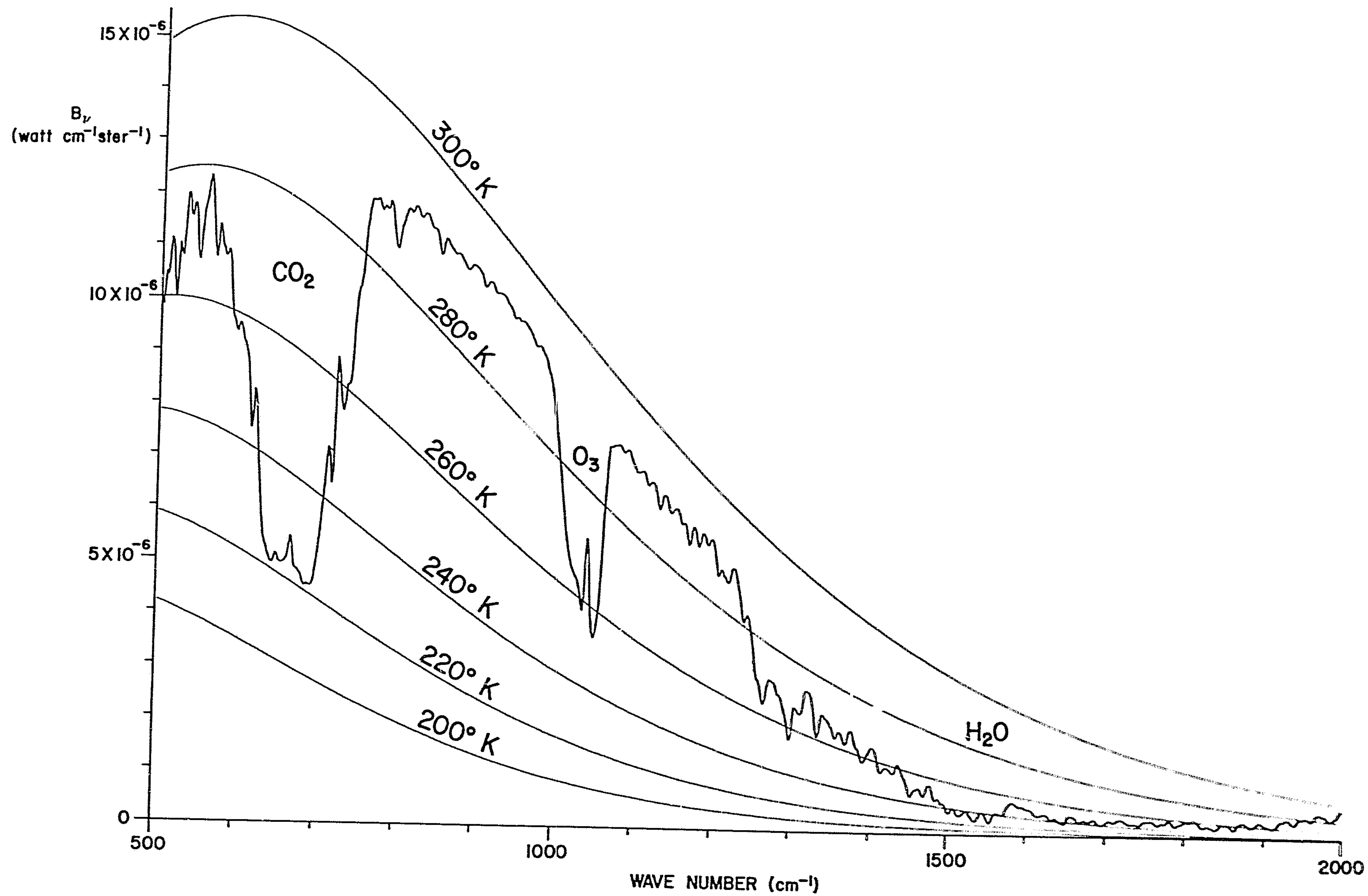

Figure 7. Spectrum of the atmosphere obtained with an Infrared Interferometer Spectrometer from a balloon at an altitude of about 31 km over Texas, May 1966. The measurement was provided by R. A. Hanel, Goddard Space Flight Center and L. Chaney, Univ. of Michigan.

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